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ARTIFICIAL ELECTRON-BELT RADIATION PROTECTION FOR

THE EXPLORER XVI SOLAR CELL POWER SUPPLY

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INTRODUCTION

The presence of a new artificial radiation belt, caused by the high-altitude nuclear explosion of July 9, 1962, posed a severe and essentially unanticipated radiation hazard to the solar cell power supply of the Explorer XVI Micrometeoroid Satellite. This hazard was demonstrated by the marked increase in the degradation rate of the solar cells on Transit 4B and Traac satellites (ref. 1). By September 1962 sufficient data had been assembled to make rough estimates of the properties of the new radiation belt. It was found to consist primarily of high-energy electrons with an approximate fission energy spectrum. An average flux of  $7.4 \times 10^{12}$  electrons/cm<sup>2</sup> per day was estimated by Goddard Space Flight Center for Explorer XVI in its predicted orbit.

There was inadequate time for a complete redesign of the power supply to provide more capacity as an allowance for increased radiation damage or to change to more radiation-resistant N-on-P solar cells. Fortunately, improvements in the Scout booster permitted the increased weight of additional shielding. An experimental program was rapidly conducted to help establish the additional window thickness required, and to qualify the types of fused quartz that could be procured rapidly. Samples of the Explorer XVI solar cells and prospective shielding materials were irradiated with 1.2 Mev electrons, both by themselves as well as

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in combination, using the Langley Research Center electron accelerator. Total doses up to  $2.7 \times 10^{15}$  electrons/cm<sup>2</sup> (1 year at  $7.4 \times 10^{12}$  electrons/cm<sup>2</sup> per day) were employed.

Figure 1 is a drawing of a typical Explorer XVI solar cell tray and its mounting arrangement, after the new 3/16-inch-thick windows were installed. It will be noted the 1/8-inch-thick magnesium tray base, the 1/10-inch-thick aluminum heat-transfer band, and the vehicle itself give adequate shielding in back of the cells against space radiation. Prior to the increase in space radiation it was estimated that the output of the cells would be decreased approximately 12 percent in 1 year, due primarily to high-energy protons penetrating, but not darkening, the original 1/16-inch-thick fused quartz windows. This estimate was supported by tests of the cells and windows in several proton accelerators.

#### DESCRIPTION OF TESTS

The accelerator used in these tests was a constant-potential, cascaded-rectifier type, Radiation Dynamics Model No. P.E.A. - 1.0. The experimental setup is shown in figure 2. The electron beam enters from the accelerator and is scanned vertically at a rate of about 10 cycles per second by the scan magnets. Next, the beam passes through a 2-mil titanium window which is blower cooled. The beam then travels about 4 inches in air to the sample tray where the samples are mounted. The position of the beam was established by using polyvinyl chloride film which turns dark when irradiated. Uniformity of the beam intensity was measured through the use of cobalt glass dosimetry. An area of approximately 4 by 12 inches was found to be uniform to  $\pm 5$  percent. Current density was monitored by using a 1- by 2-centimeter aluminum pickup which passed the current received through an electrometer to ground. In addition, the sample tray and support were

grounded to prevent any change in their potential. The energy used in these tests, as measured by the extreme range of electrons in aluminum at the location of the samples, was 1.2 Mev. The beam-current density was held constant at 0.03 microampere per square centimeter in order to minimize heating effects. The measured temperature rise under these conditions was 5° to 8° F. Because of the small heating, no auxiliary sample cooling was employed.

The solar cells tested were nominally 8 percent efficient, P-on-N type, and 1 by 2 centimeters in size. Four cells, randomly selected from those purchased for Explorer XVI, were used in each test. To simulate the actual vehicle mounting arrangement (fig. 1) each cell was cemented to a 1/8-inch-thick Dow 17 coated magnesium strip with RTV-40 cement. When shields were employed, they were spaced the same distance above the cells as in the vehicle arrangement. During the irradiation tests, the magnesium strips were directly attached to the aluminum sample tray (fig. 2). Before irradiation and after each dose, the cells were evaluated with the shields, if any, removed. Tungsten lights with filament temperatures at 2,800° K were used, and the cell loading was varied from short circuit to open circuit. Spectral response curves were also obtained to relate the measurements to space sun.

The samples of transparent shielding materials were spaced 3/32 inch above the aluminum sample tray during the irradiation tests which involved only these materials. Before and after each irradiation dose a typical nonirradiated solar cell was used to measure the broad band percent light transmission in the spectral range of interest with an accuracy of approximately 1/2 percent. Spectral transmission curves were also made over the spectral range of 4,500 to 25,000 angstroms.

## RESULTS AND DISCUSSION

Figure 3 shows the effect of electron irradiation at 1.2 Mev on the power output of bare and shielded solar cells. This figure shows the percent reduction of initial output power at 0.375 volt, and corrected for the spectral distribution of space sunlight, plotted as a function of total dose. Data are shown for the bare cells and for cells which had been shielded with two different thicknesses of quartz. The curves are drawn through the average of the points for the four cells used in each test. The degradation of the bare cells approximated that obtained in previous Langley tests and that obtained by others (ref. 2) for similar cells. In this case the data were taken under conditions identical to those for the shielded cells.

One feature that is surprising is the degree of damage done to the solar cell behind the 3/16-inch-thick quartz shield. The weight of this shield is 1.05 gm/cm<sup>2</sup> and it is quite adequate to stop all of the electrons used in this particular test. It will be observed that the average power output is reduced by about 7.5 percent at a total dose of  $2.7 \times 10^{15}$  electrons/cm<sup>2</sup>. Unless scattering was considerably greater than expected, this degree of damage is surprising because the bremsstrahlung efficiency at this energy and in the relatively lightweight silicon is quite low. Thus it may well be that the effectiveness of the bremsstrahlung radiation at this energy is greater than previously estimated (ref. 2). As a practical result, this may mean that it is impossible to completely protect an extremely radiation-sensitive type of cell. Also it should be noted that the degree of damage done to the cell shielded by 1/16-inch-thick quartz is not as great as would be expected. Range measurements indicate that there should be approximately 52 percent transmission through a 1/16-inch-thick

quartz shield (ref. 3). However, of this 52 percent that get through, it can be deduced from damage data that only about 3 percent get through with energies sufficiently above the damage threshold.

The second surprising feature of the test results was the vast difference in darkening of similar quartzes under irradiation. Figure 4 illustrates this with a photograph showing four different samples. Each had a different trade name but all were manufactured by fusing crystalline quartz. Sample number 2 in this photograph was the quartz originally intended for use on the Explorer XVI. With previous tests under proton irradiation simulating a 1-year dose, no darkening was observed. In the present tests the light transmission of this particular quartz was reduced by approximately 10 percent.

Figure 5 gives a more quantitative indication of the manner in which the quartz darkens. The figure shows the change in light transmission as measured with a solar cell plotted against total dose. The particular curves shown here do not correspond directly with the photograph shown previously; however, they are quite representative of the wide variety of the quartzes tested. It will be observed from the lowest curve that a quartz which will darken severely will do so very early during its exposure to electron radiation. Thus, a short expected lifetime in space is not a suitable reason for selecting the shielding material without reference to radiation sensitivity. In each case where darkening was noted, the spectral transmission curves indicated a broad absorption band centered at 5,500 angstroms.

A reasonably large number of quartzes were found which did not darken at all under irradiation. In each case these were made by a vapor deposition method and are often called synthetic fused quartz. The quartz finally chosen, Corning #7940, was selected from among these primarily on the basis of rapid availability.

Samples of sapphire such as were used on "Telstar" were also tested and showed no degradation in transmission of light. The reason that quartz was used in preference to sapphire is twofold: first, the design, which was already fixed, required larger pieces of shielding material than could be obtained in sapphire; and second, sapphire is decidedly more expensive than quartz.

#### ESTIMATED LIFETIME IN SPACE OF EXPLORER XVI SOLAR CELLS

In translating the present test results into lifetime in space, the following assumptions were made:

1. The average omnidirectional flux was  $7.4 \times 10^{12}$  electrons/cm<sup>2</sup>-day.
2. The solar cells will be exposed to half the total flux because of the heavy shielding behind them. A geometric argument can be used to justify still another factor of 2; this has not been used since the following assumption has already been shown to be unconservative.
3. Bremsstrahlung radiation has not been considered.
4. The fission energy can be used to represent the energy spectrum of all the electrons.
5. The fraction of electrons transmitted through 3/16 inch of quartz (1.05 gm/cm<sup>2</sup>) is 1/13 and through 1/16 inch of quartz is 1/2.5 (ref. 4).
6. The solar cell damage rate is the same as that measured at 1.2 Mev.

Figure 6 shows the predicted decrease of initial output plotted against time for the bare cells as well as those with 1/16-inch- and 3/16-inch-thick quartz shields. The preceding assumptions and the above-described tests on the bare cells were used in preparing the figure. If the original 1/16-inch windows had been used, the solar cell output would probably have dropped to the minimum power required to operate the electronics before the expected lifetime of 1 year. With

the present 3/16-inch windows it can be seen that the solar cells will supply the required output for at least the expected lifetime.

#### SPACE DEGRADATION OF SOLAR CELLS ON EXPLORER XVI

On December 16, 1962 Explorer XVI was injected into an earth orbit with nearly the same parameters as the orbit used when estimating the expected radiation dose. The actual orbital parameters are: perigee 750 km, apogee 1,180 km, and inclination 52°. On March 26, 1963, after 100 days in orbit, a test group of unprotected solar cells showed a degradation of approximately 23 percent. This compares with the predicted value of 40 percent shown in figure 6. At the same time another test group of cells, protected with 3/16-inch-thick fused quartz windows in the same manner as the power cells, showed a degradation of about 3 percent compared with the predicted value of 13 percent shown in figure 6.

The lower degradation is comforting, and can be at least partially explained. Some decay of the electron flux at the lower orbital altitudes of Explorer XVI has occurred. In March 1963 Goddard Space Flight Center reestimated the flux encountered by Explorer XVI using the data available at that time. An average dose of  $2.3 \times 10^{12}$  electrons/cm<sup>2</sup> per day was obtained, down by a factor of 3.2 from that originally estimated. If this flux value had been used to prepare figure 6, a degradation of 33 percent would have been predicted for the unprotected cells, still somewhat greater than that measured.

#### CONCLUSIONS

In summary this study of increased radiation protection for the Explorer XVI power supply indicates the following general conclusions:

1. It is possible to suitably protect even older type P-on-N cells to the point where service lifetimes greater than 1 year in the artificial radiation belt may be obtained.

2. Bremsstrahlung damage may possibly be greater than has been previously estimated, thus making it impossible to totally shield extremely radiation-sensitive solar cells.

3. Of the 1.2 Mev electrons that are transmitted through a 1/16-inch-thick quartz shield, only a small percent get through with energy greater than the damage threshold of silicon.

4. Small differences in quartz make major differences in darkening under irradiation; however, the samples of synthetic fused quartz obtained from several manufacturers did not perceptually darken in the spectral range of interest.

5. Those quartzes which darken severely do so in the early part of the dose.

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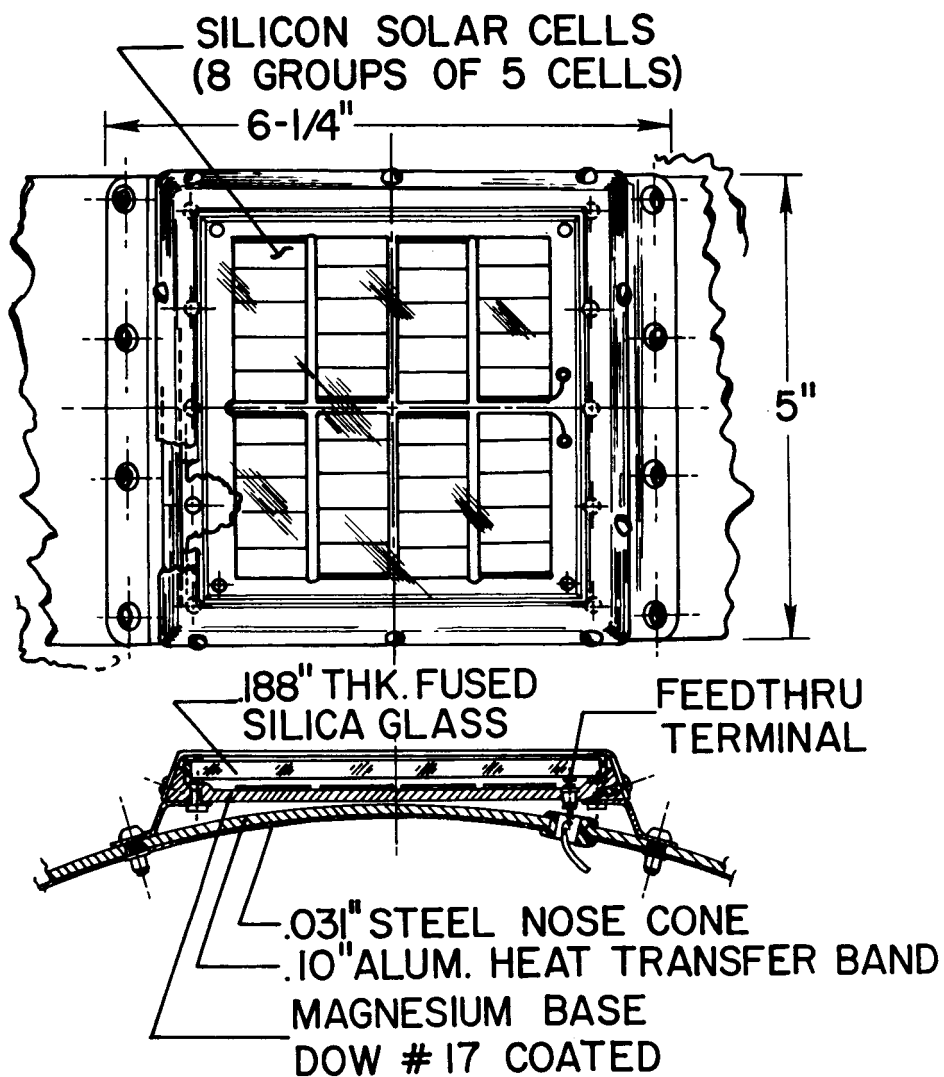
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Figure 1.- Power solar cell unit.

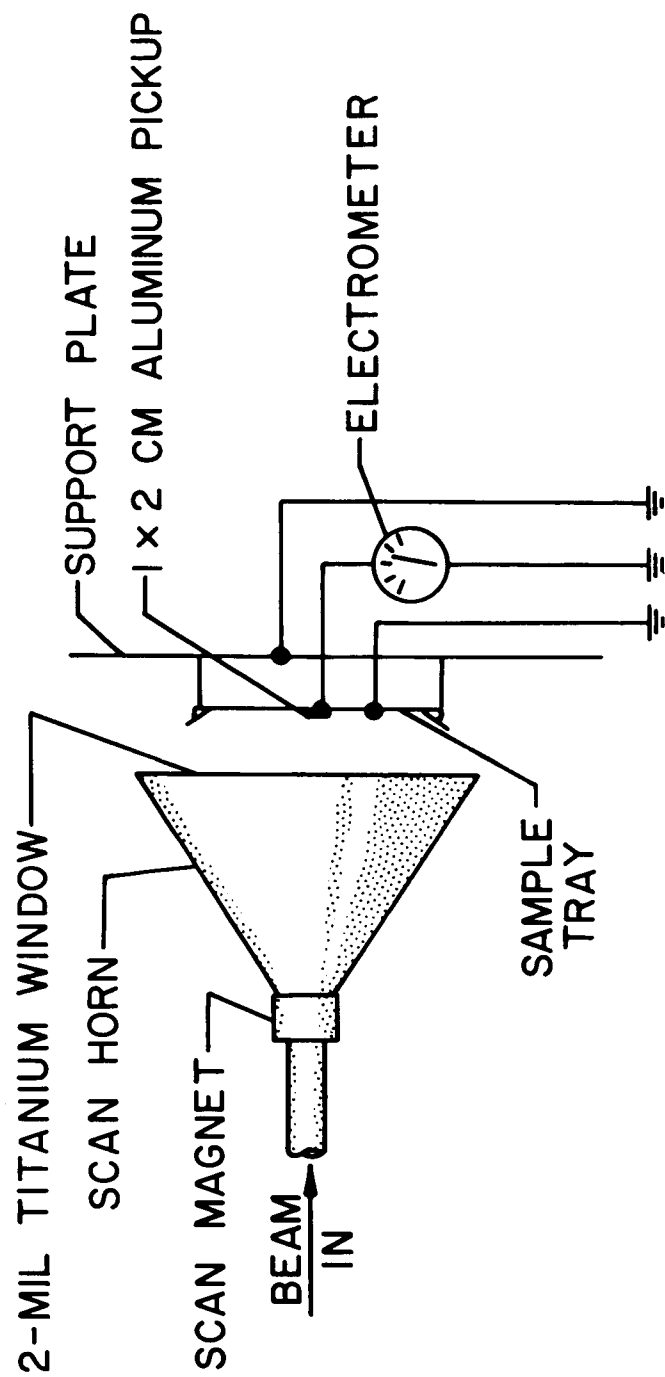
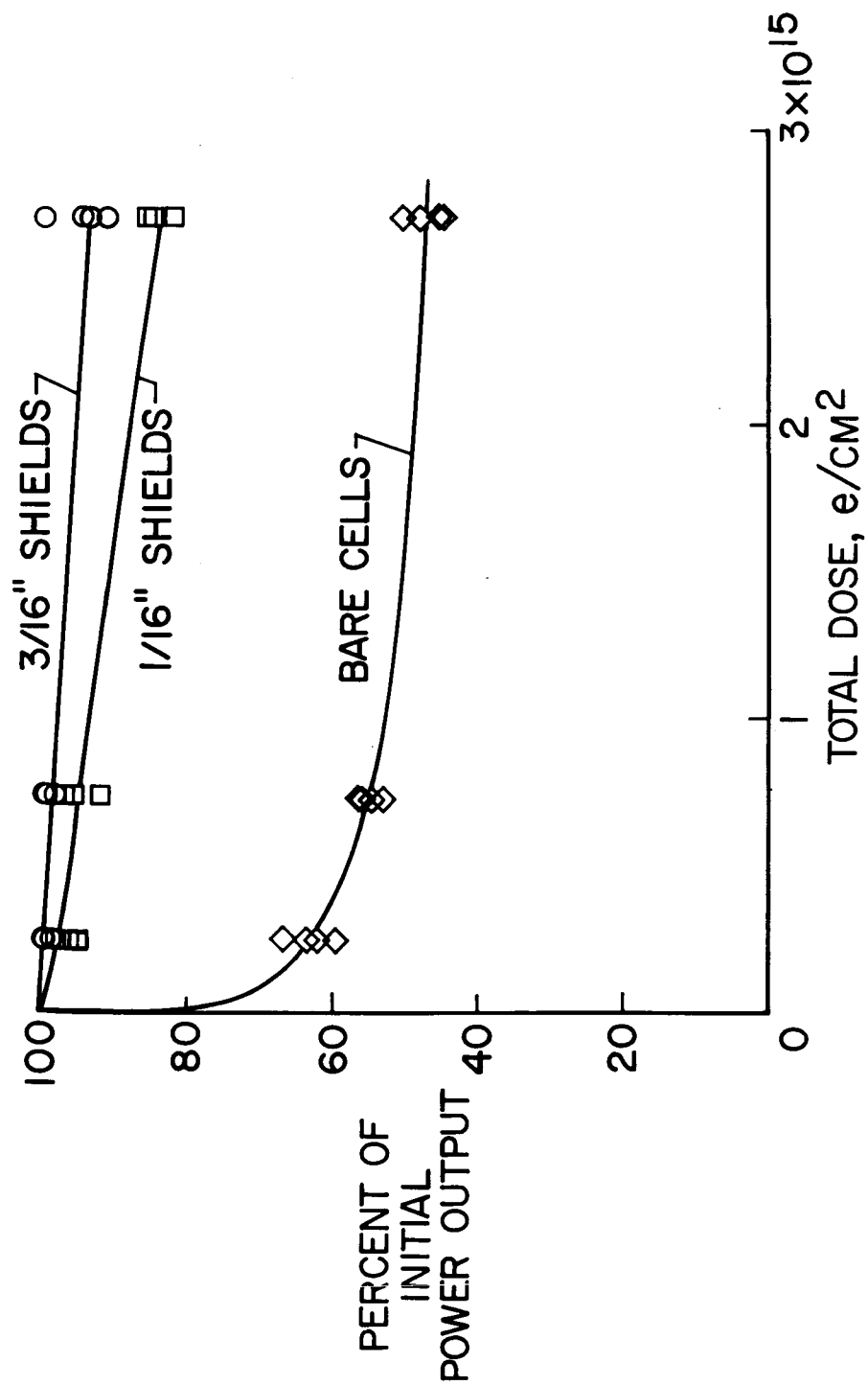


Figure 2.- Experimental arrangement.



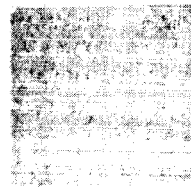
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Figure 3.- Effect of 1.2-mev electrons on bare and shielded cells.

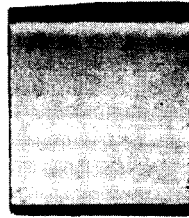


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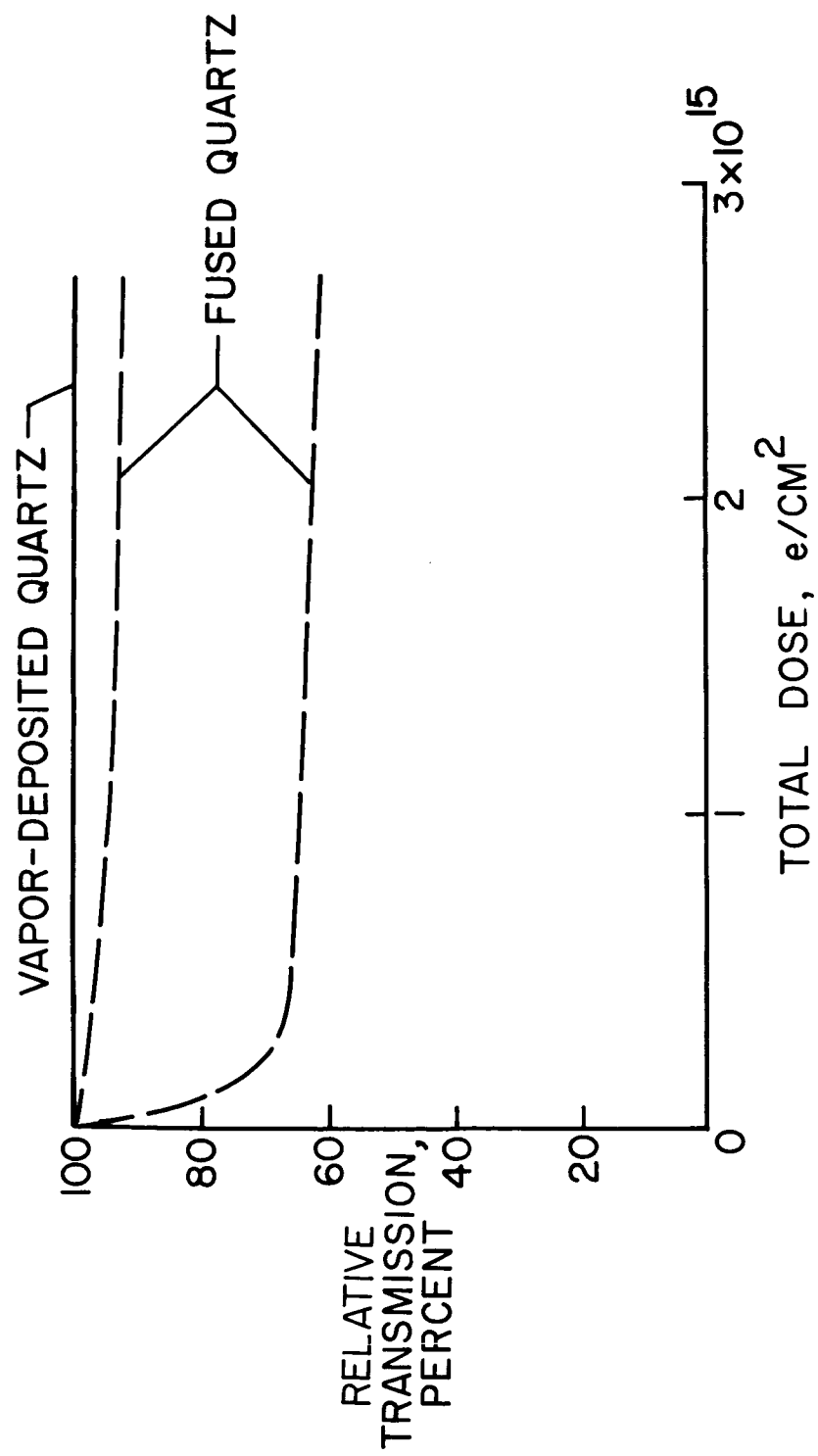
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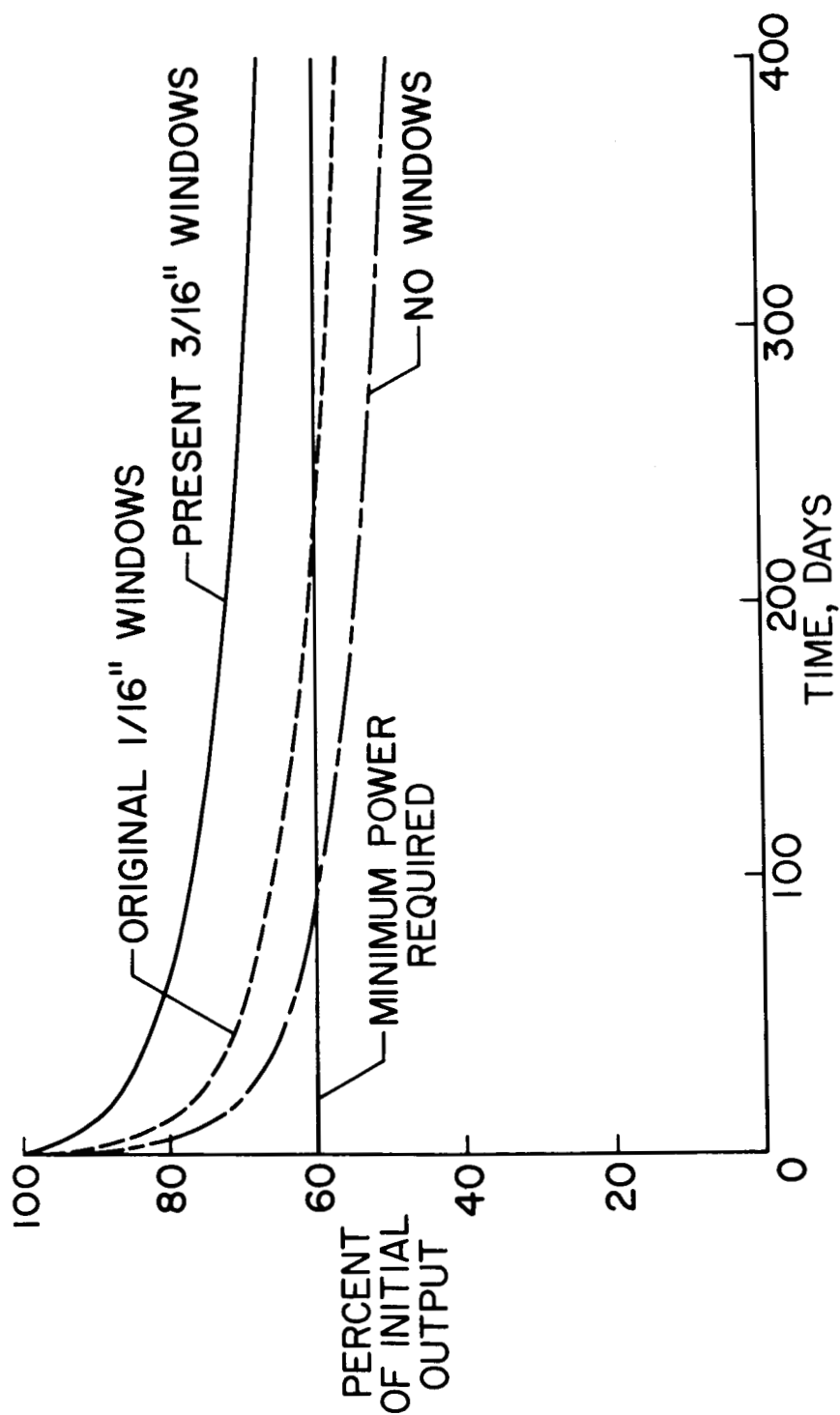
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Figure 4.- Irradiated fused quartz.



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Figure 5.- Degradation of quartz window.



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Figure 6.- Effect of shielding on lifetime of power supply.